

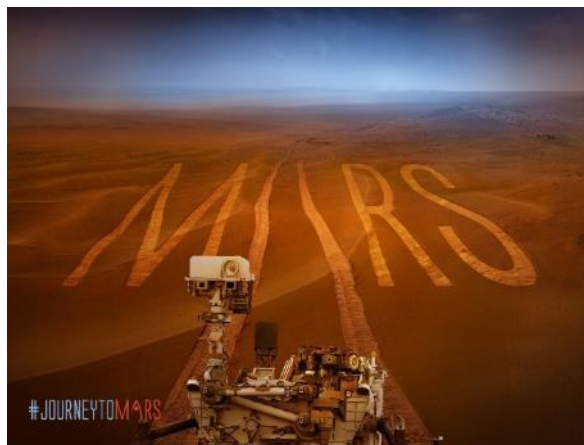
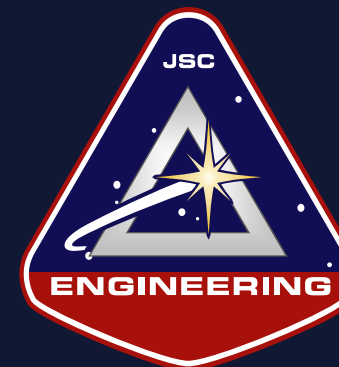


Johnson Space Center Engineering Directorate L-8: In-Situ Resource Utilization (ISRU) Capabilities

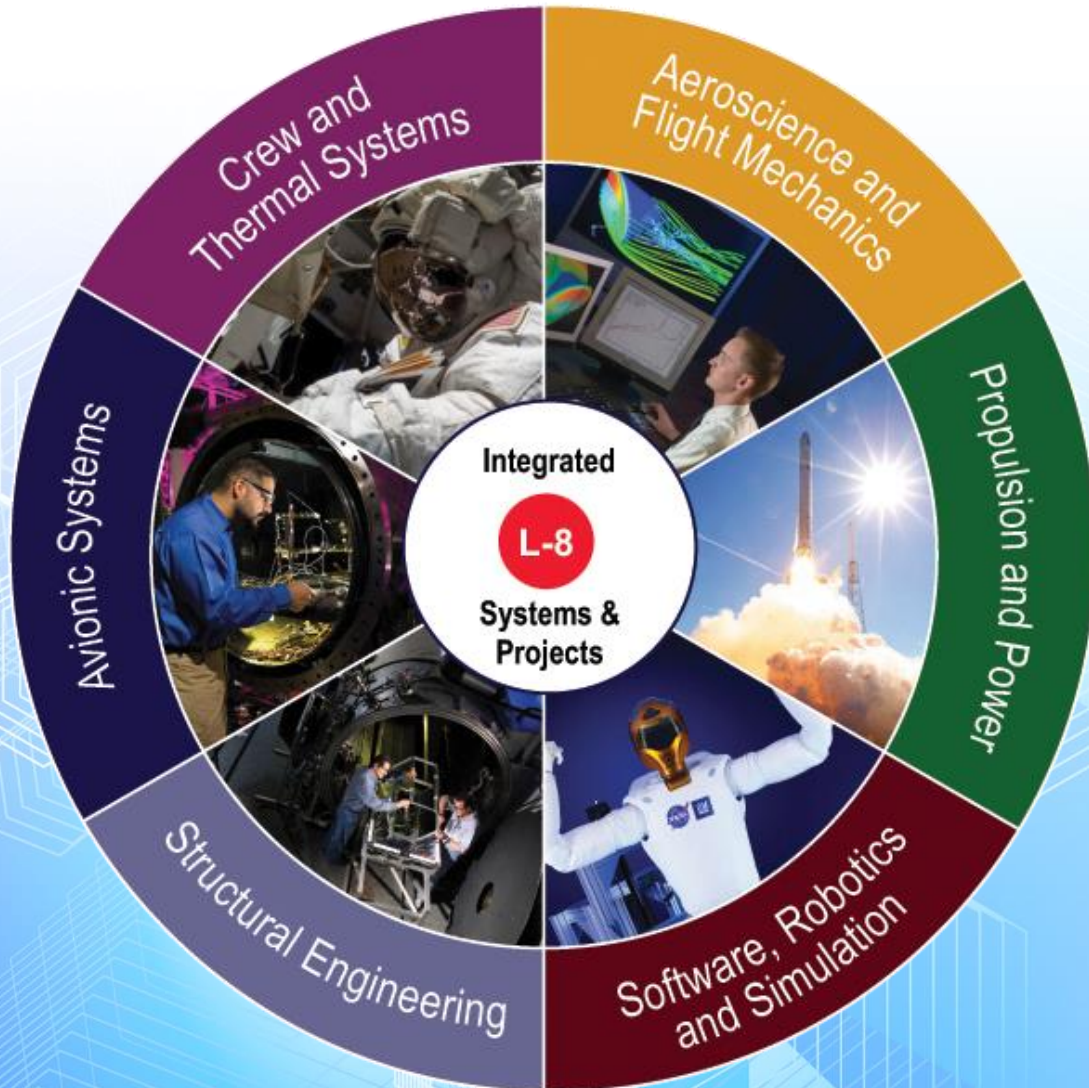
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Jerry Sanders
November 2016



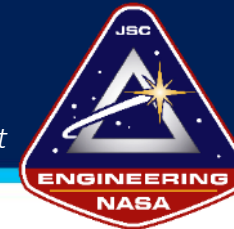
JSC Engineering: HSF Exploration Systems Development



- We are sharpening our focus on Human Space Flight (HSF) Exploration Beyond Low Earth Orbit
- We want to ensure that HSF technologies are ready to take Humans to Mars in the 2030s.
 - Various Roadmaps define the needed technologies
 - We are attempting to define our activities and dependencies
- Our Goal: Get within 8 years of launching humans to Mars (L-8) by 2025
 - Develop and mature the technologies and systems needed
 - Develop and mature the personnel needed
- This is one of a number of specific partnership opportunities that you might be interested in to discuss during SpaceCom 2016.

EA Domain Implementation Plan Overview

JSC Engineering: HSF Exploration Systems Development



- Life Support
- Active Thermal Control
- EVA
- Habitation Systems

- Human System Interfaces
- Wireless & Communication Systems
- Command & Data Handling
- Radiation & EEE Parts

- Lightweight Habitable Spacecraft
- Entry, Descent, & Landing
- Autonomous Rendezvous & Docking
- Vehicle Environments



- Entry, Descent, & Landing
- Autonomous Rendezvous & Docking
- Deep Space GN&C

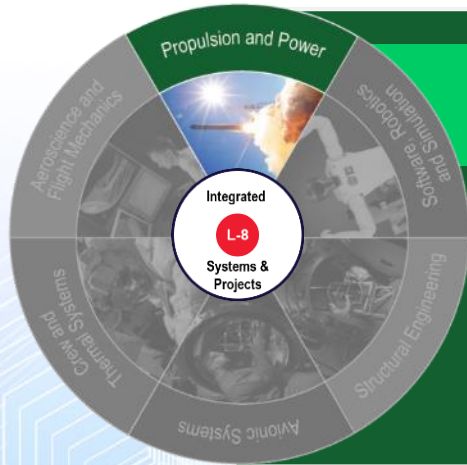
- Reliable Pyrotechnics
- Integrated Propulsion, Power, & ISRU
- Energy Storage & Distribution
- Breakthrough Power & Propulsion

- Crew Exercise
- Simulation
- Autonomy
- Software
- Robotics

AA-2 | iPAS | HESTIA | Morpheus

Propulsion and Power Challenge

JSC Engineering: HSF Exploration Systems Development



- Integrated Propulsion, Power, & ISRU
- Reliable Pyrotechnics
- Energy Storage & Distribution
- Breakthrough Power & Propulsion

In-Situ Resource Utilization Capabilities

- NASA is developing technologies, systems, & operations to:
 - Find, extract, and process *in situ* resources
 - Store, transfer, and distribute products
 - Perform extraterrestrial civil engineering & construction
- To maximize the benefits and minimize the mass and development costs, NASA is developing propulsion and power systems, which can be integrated with life support and thermal management systems, that use common ISRU-derived reactants and storage
- Developing and incorporating ISRU into human missions faces many of the same technology, infrastructure, environment, and deployment needs and challenges as the terrestrial mining, chemical processing, construction, and energy industries
- NASA hopes to partner by spinning-in and off technologies, operations, and best practices with industry through BAAs, CANs, SAAs, and SBIRs.

The Problem

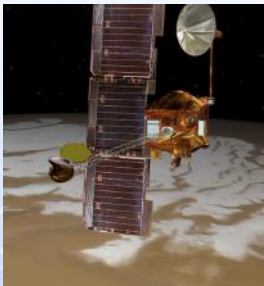
- For every 1 kg landed on Mars, 7.5 to 11 kg has to be launched into orbit from Earth.
- 23 mT of oxygen and 6.5 mT of methane propellants are needed for the Mars crewed ascent vehicle. This equates to the payload mass of 3 to 5 SLS launches
- Propulsion, power, and life support systems need to be designed from the start to use ISRU products
- Current ISRU technologies and systems are subscale engineering breadboards with limited space/Mars environmental testing

What is *In Situ* Resource Utilization (ISRU)?



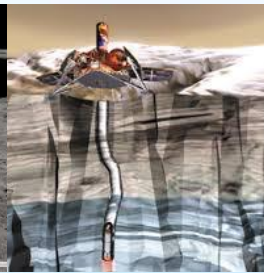
ISRU involves any hardware or operation that harnesses and utilizes 'in-situ' resources to create products and services for robotic and human exploration

Resource Assessment (Prospecting)



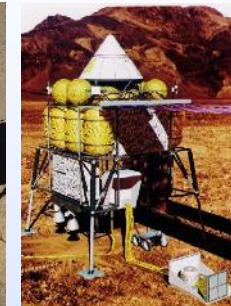
Assessment and mapping of physical, mineral, chemical, and volatile/water resources, terrain, geology, and environment

Resource Acquisition



Extraction, excavation, transfer, and preparation/beneficiation before Processing

Resource Processing/ Consumable Production



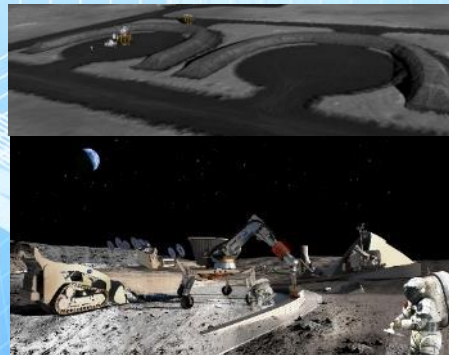
Processing resources into products with immediate use or as feedstock for construction and/or manufacturing
➤ Propellants, life support gases, fuel cell reactants, etc.

In Situ Manufacturing



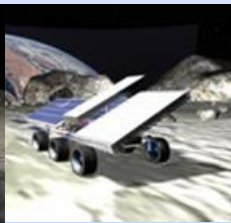
Production of replacement parts, complex products, machines, and integrated systems from feedstock derived from one or more processed resources

In Situ Construction



Civil engineering, infrastructure emplacement and structure construction using materials produced from in situ resources
➤ Radiation shields, landing pads, roads, berms, habitats, etc.

In Situ Energy



Generation and storage of electrical, thermal, and chemical energy with in situ derived materials
➤ Solar arrays, thermal storage and energy, chemical batteries, etc.

- **'ISRU' is a capability involving multiple elements to achieve final products** (mobility, product storage and delivery, power, crew and/or robotic maintenance, etc.)
- **'ISRU' does not exist on its own.** By definition it must connect and tie to users/customers of ISRU products and services

ISRU Integrated with Exploration Elements

Mission Consumables



ISRU Functions & Elements

- Resource Prospecting/Mapping
- Excavation
- Regolith Transport
- Regolith Processing for:
 - Water/Volatiles
 - Oxygen
 - Metals
- Atmosphere Collection
- Carbon Dioxide/Water Processing

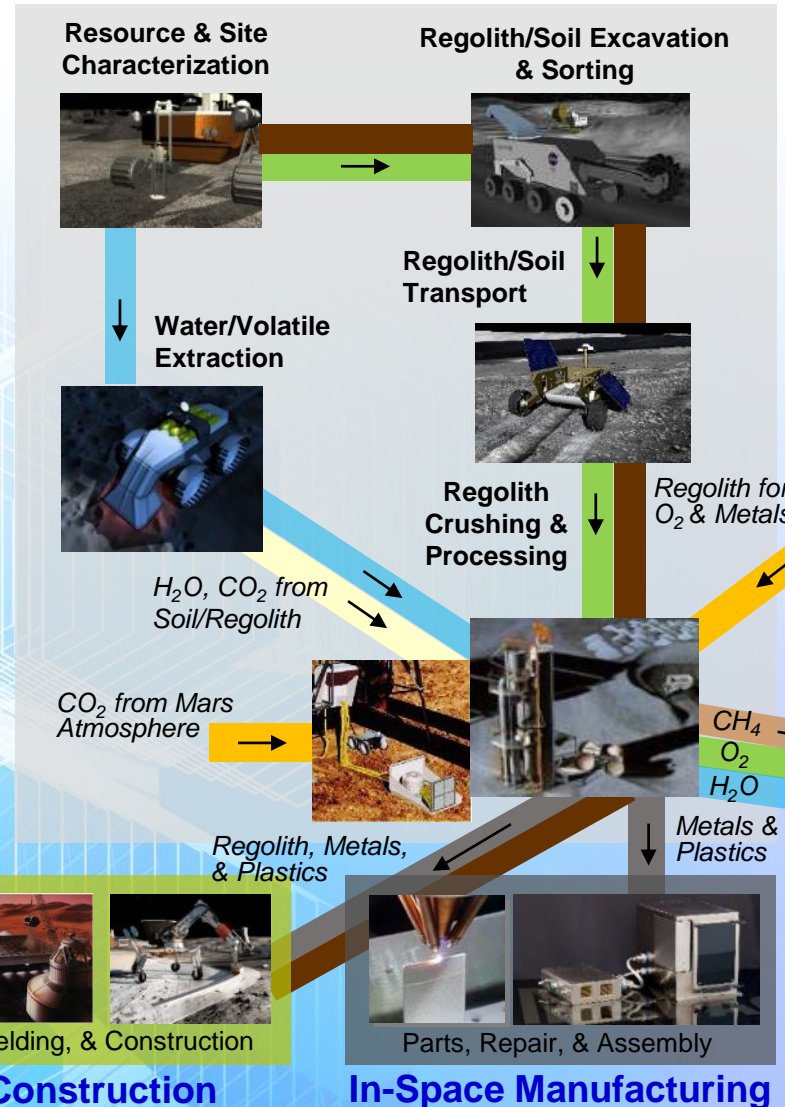
Support Functions & Elements

- Power Generation & Storage
- O₂, H₂, and CH₄ Storage and Transfer

Potentially Shared Hardware to Reduce Mass & Cost

- Solar arrays/nuclear reactor
- Water Electrolysis
- Cryogenic Storage
- Mobility

ISRU Resources & Processing



Life Support & EVA



CO₂ & Trash/Waste

Habitats



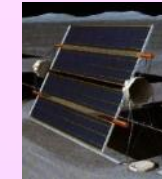
Used Descent Stage



Propellant Depot

Storage

Modular Power Systems



Solar & Nuclear



Regenerative Fuel Cell



Surface Hopper



Lander/Ascent

Lander/Ascent

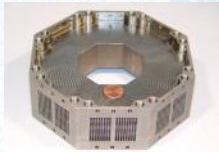
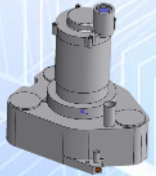
ISRU Processes and Products

Mission Consumables - *Lab and Pilot Scale for Industry*



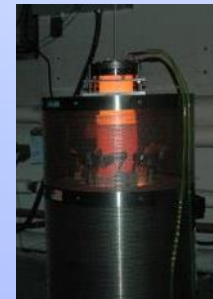
Atmosphere Processing

- Dust Filtration
- Gas Separation (CO_2 , N_2 , Ar)
- Gas Pressurization (0.1 to >15 psia)
 - Pumps/Compressors
 - Cryogenic Separation
 - Adsorption



Chemical Processing

- CO_2 Reduction
 - Solid Oxide Electrolysis
 - Reverse Water Gas Shift
 - Bosch
- Fuel Production
 - Sabatier (CH_4)
 - Fischer Tropsch
 - Alcohols
 - Ethylene \rightarrow Plastics
- Water Processing
 - Water Electrolysis (PEM vs SOE)
 - Water Cleanup/Deionization



Solid Processing

- Regolith Excavation/Extraction
 - Drills/Augers (1 to 3 m)
 - Load/Haul/Dump
 - Bucketwheels/Drums
- Regolith/Soil Transfer
 - Augers
 - Pneumatic
 - Bucket ladders
- Water/Volatile Extraction
 - Hydrated soils
 - Icy soils
- Trash/Waste Processing
 - Steam Reforming/Oxidation
 - Pyrolysis
- Oxygen Extraction from Minerals
 - Hydrogen Reduction of Iron Oxides
 - Methane Reduction of Silicates
 - Molten Oxide Reduction
- Metal Extraction from Minerals
 - Molten Oxide Reduction
 - Ionic Liquid Acids
 - Biological Extraction

Potential Lunar Resource Product Needs

- 2,000 kg oxygen (O_2) per year for life support backup (crew of 4)
- 3,500 kg of O_2 per lunar ascent module launch from surface to low lunar orbit
- 16,000 kg of O_2 per reusable lunar lander ascent/descent vehicle to L1/L2 (fuel from Earth)*
- 30,000 kg of O_2 /Hydrogen (H_2) per reusable lunar lander to L1/L2 (no Earth fuel needed)*

Potential Mars Resource Product Needs

- 20,000 kg to 25,000 kg of oxygen (O_2) per ascent mission (~2 kg/hr)
- 5700 kg to 7150 kg of methane (CH_4) per ascent mission
- 14,200 kg of water (H_2O) per ascent mission

**Note: ISRU production numbers are only 1st order estimates for 4000 kg payload to/from lunar surface*

ISRU Processes and Products

Construction: Roads, Landing Pads, Structures, Plume Protection



Area Leveling/Grading/Berms



Autonomous & Tele-operation



Additive Construction



Sintered/Fabricated Pavers



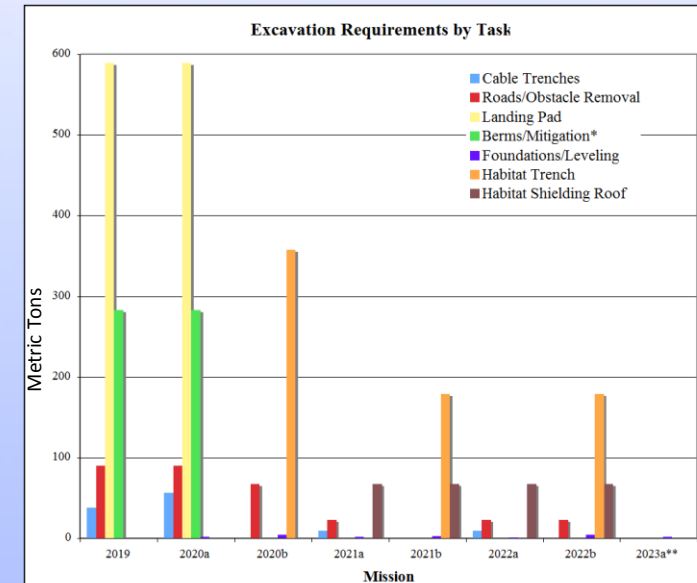
Surface & Subsurface Evaluation



Combustion Synthesis



Waterless Concrete



ISRU is Similar to Establishing Remote Mining Infrastructure and Operations on Earth



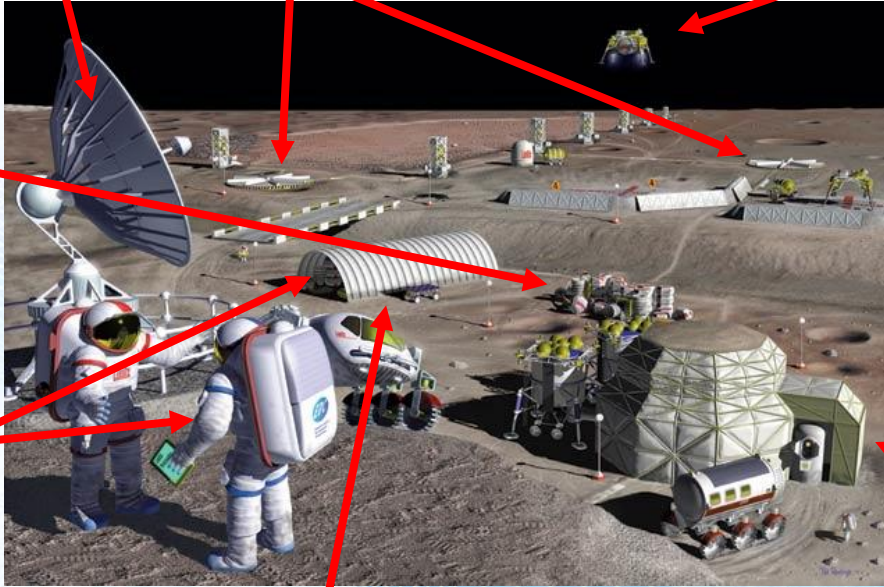
Communications

Power

Transportation to/from Site

Logistics Management

Maintenance



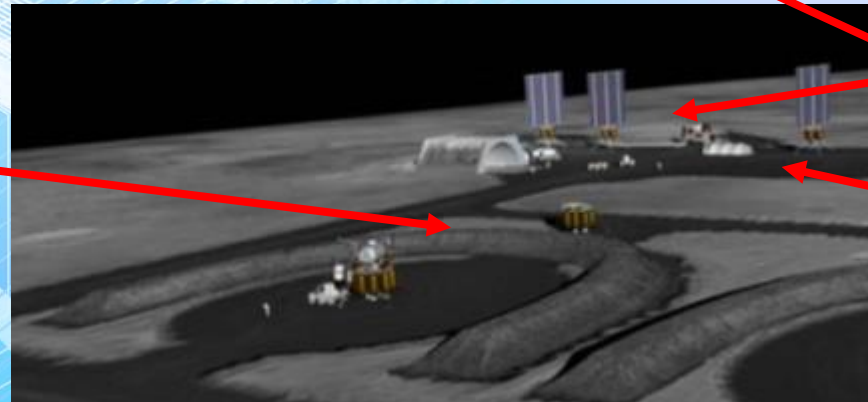
Planned, Mapped, and Coordinated Mining Ops:

- Excavation
- Processing
- Tailings

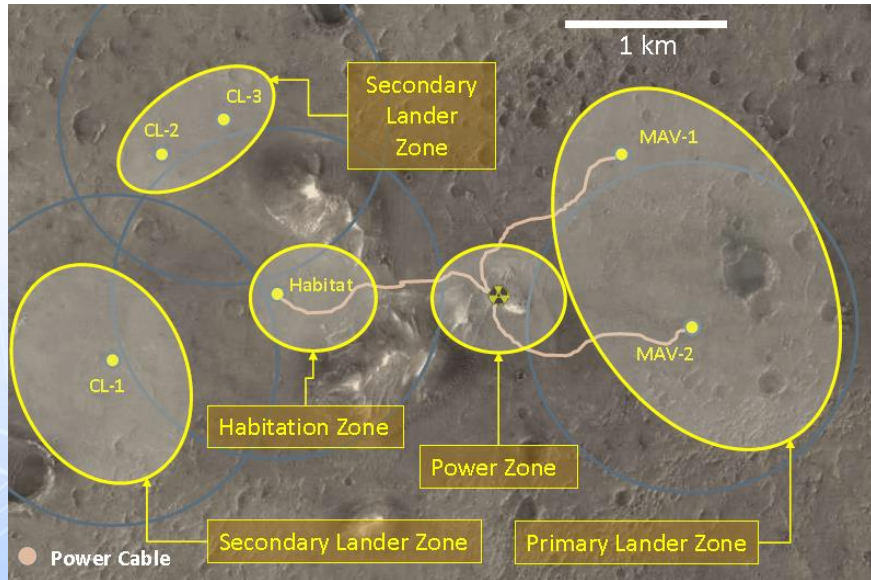
Construction and Emplacement

Living Quarters

Roads

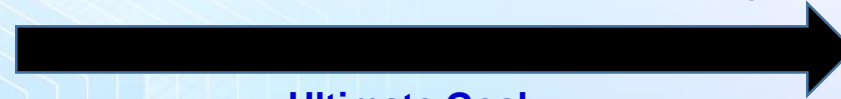


ISRU Products, Operations, and Resources Will Grow As Mission Needs and Infrastructure Grow



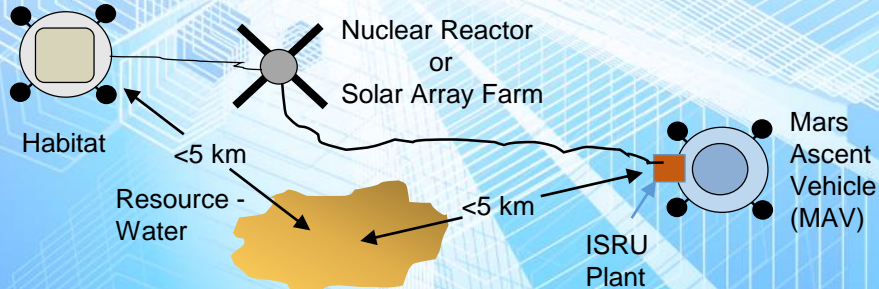
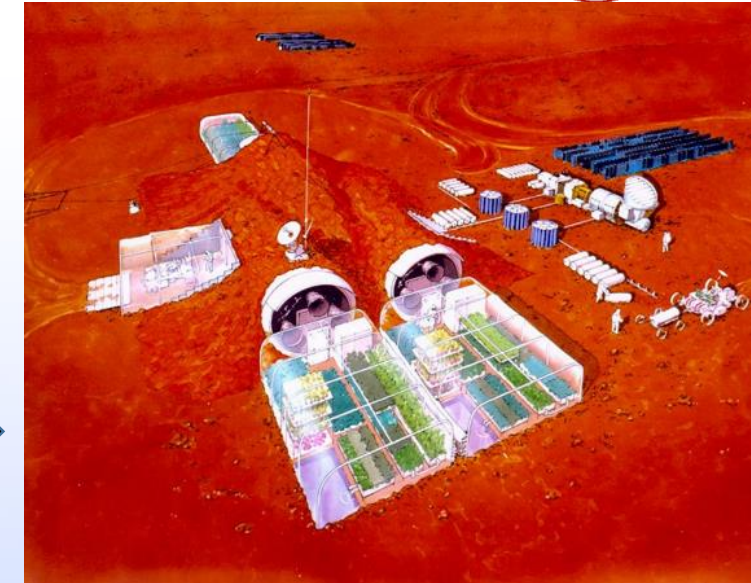
Initial Conditions:

- Hardware delivered by multiple landers before crew arrives; Multiple landing zones
- Elements offloaded, moved, deployed, and connected together remotely
- 12-18 month stay for crew of 4 to 6; Gaps of time between missions where crew is not present
- Each mission delivers extra hardware & logistics

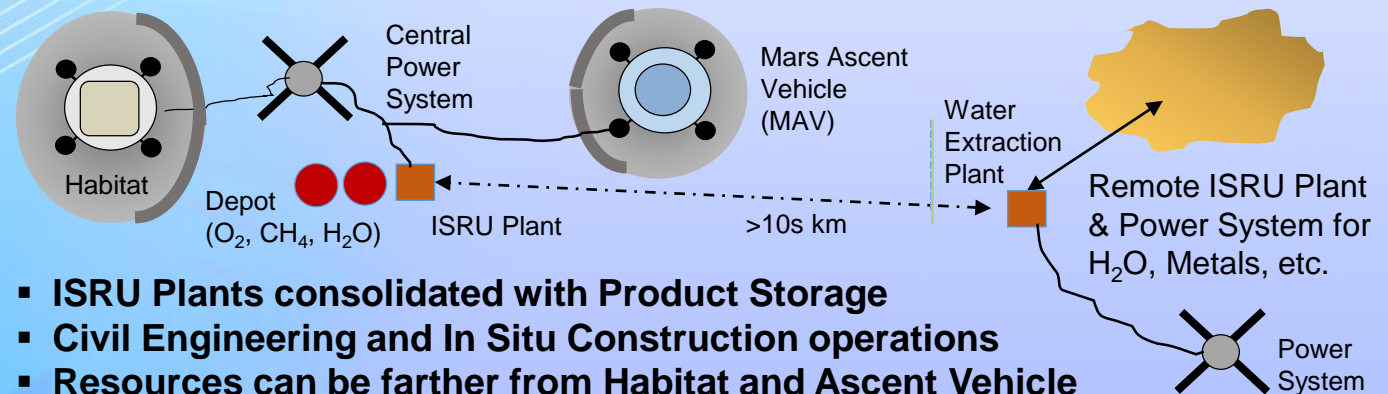


Ultimate Goal

- Consolidated and integrated infrastructure
- Indefinite stay with larger crews
- Roam (and mine) anywhere within 200 km diameter Exploration Zone
- Earth independent; *In situ* ability to grow infrastructure: power, habitation, food, parts, etc.



- ISRU hardware integrated with Landers
- Resource very close to landing site/Ascent vehicle

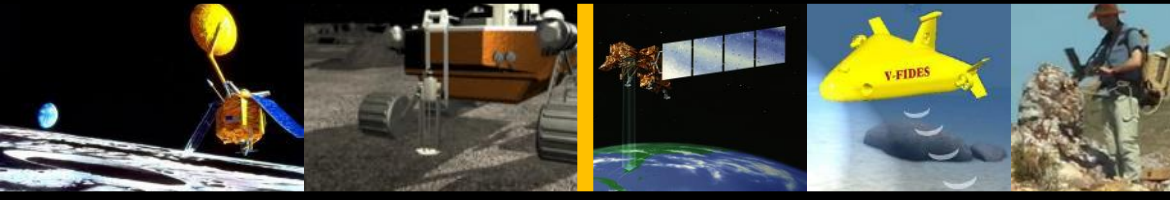


- ISRU Plants consolidated with Product Storage
- Civil Engineering and In Situ Construction operations
- Resources can be farther from Habitat and Ascent Vehicle

There are A lot of Similarities between ISRU and Terrestrial Applications



Prospecting for Resources



Mining for Resources



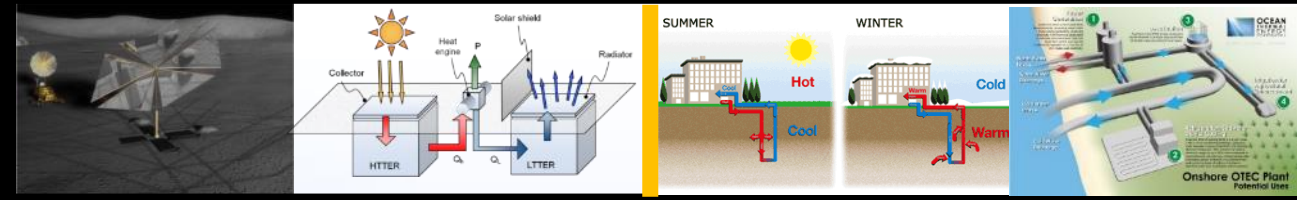
Resource Processing (Gases, Liquids, Solids)



Civil Engineering & Construction



Thermal Energy



Alternative Energy (Fuel Cells & Trash to HC)



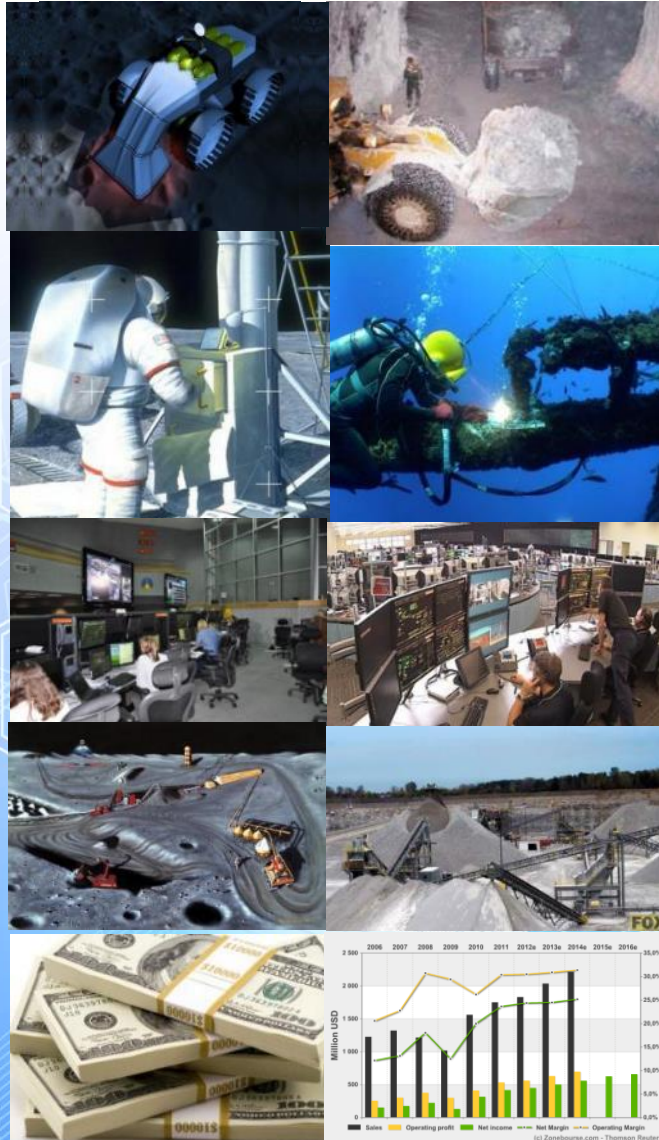
Product Liquefaction, Storage, and Transfer



Remote Operations & Maintenance



ISRU Has Common Challenges with Terrestrial Industry



Severe Environments

- Extreme temperatures
- Large changes in temperature
- Dust and abrasion
- No pressure vs Extreme pressure
- Environmental testing

Maintenance

- Minimal maintenance desired for long operations
- Performing maintenance is difficult in environments
- Minimize logistics inventory and supply train

Operations/Communication

- Autonomous and tele-operation;
- Delayed and potentially non-continuous communication coverage
- Local navigation and position information

Integration and Infrastructure

- Hardware from multiple countries must be compatible with each other
- Common standards; Common interface
- Optimize at the architecture/operation level vs the individual element
- Establish and grow production and infrastructure over time to achieve immediate and long-term Returns on Investment

Return on Investment

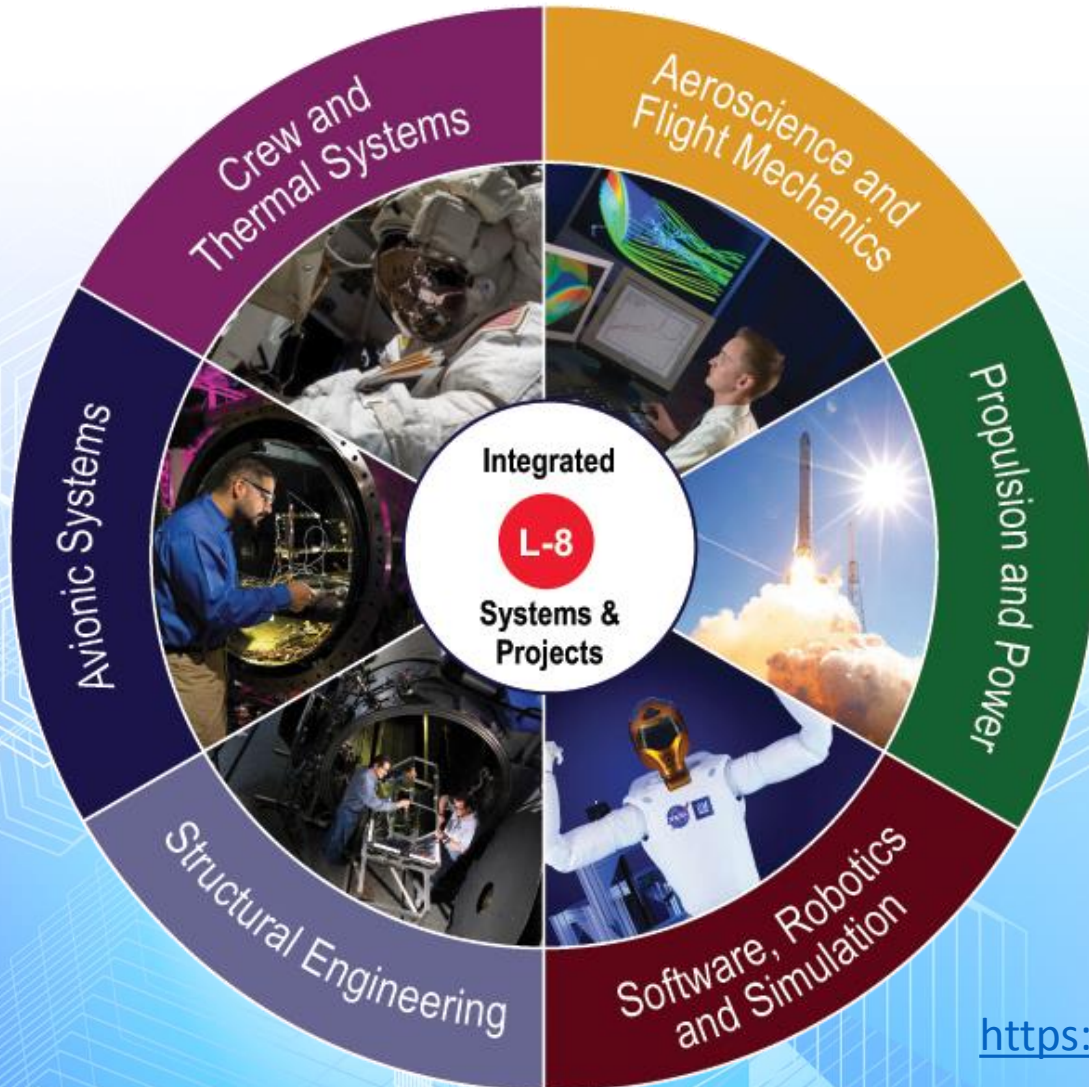
- Need to have a return on investment to justify expense and infrastructure buildup
- Multi-use: space and terrestrial applications

ISRU: Where We Are Today



- Most Prospecting, Excavation, and Consumable Production technologies, systems, and technologies have been shown to be feasible at subscale and for limited test durations
- Drivers
 - Hardware simplicity and life are as important as minimizing mass and power
 - Hardware commonality with other systems (propulsion, power, life support, thermal) can significantly reduce costs and logistics
- Work still required to:
 - Scale up production and processing rates to human mission needs (*lab and pilot scale for terrestrial industry*)
 - Operate hardware and systems under relevant mission environments; Understand how to take advantage of the environment and day/night cycle
 - Perform long-duration testing to understand hardware life, maintenance, and logistics needs
 - Add autonomy to operations, especially for mining operations
- Partnering with Terrestrial Industry and co-leveraging hardware is important to NASA
 - Address common needs and challenges
 - Reduce costs and increase return on investments

JSC Engineering: HSF Exploration Systems Development



- We want to ensure that HSF technologies are ready to take Humans to Mars in the 2030s.
- Our Goal: Get within 8 years of launching humans to Mars (L-8) by 2025
- This is one of a number of specific partnership opportunities we're discussing at SpaceCom 2016.
- If you're interested in one of these, or you have other ideas, let us know at:

<https://nasajsc.secure.force.com/ConnectForm>





Backup

Space Resources and Products of Main Interest



Moon: Three major resources

- **Regolith:** oxides and metals
 - Ilmenite 15%
 - Pyroxene 50%
 - Olivine 15%
 - Anorthite 20%
- Solar wind volatiles in regolith
 - Hydrogen 50 – 150 ppm
 - Helium 3 – 50 ppm
 - Carbon 100 – 150 ppm
- **Water/ice** and other volatiles in polar shadowed craters
 - 1-10% (LCROSS)
 - Thick ice (SAR)

Mars: Three major resources

- **Atmosphere:**
 - 95.5% Carbon dioxide,
 - 2.7% Nitrogen,
 - 1.6% Argon
- **Water in soil:** concentration dependant on location
 - 2% to dirty ice at poles
- Oxides and metals in the soil

Resources of Main Interest

- Oxygen
- Water
- Hydrogen
- Carbon/CO₂
- Nitrogen
- Metals
- Silicon

Near Earth Asteroids: ~85% of Meteorites are Chondrites

Ordinary Chondrites

FeO:Si = 0.1 to 0.5
Fe:Si = 0.5 to 0.8

87%

Pyroxene
Olivine
Plagioclase
Diopside
Metallic Fe-Ni alloy
Troilite - FeS

Source of metals
(Carbonyl)

Carbonaceous Chondrites 8%

Highly oxidized w/ little or no free metal
Abundant volatiles: up to 20% bound water and 6% organic material

Source of water/volatiles



Enstatite Chondrites 5%

Highly reduced; silicates contain almost no FeO
60 to 80% silicates; Enstatite & Na-rich plagioclase
20 to 25% Fe-Ni
Cr, Mn, and Ti are found as minor constituents

Easy source of oxygen (Carbothermal)



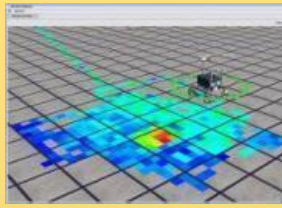
Space 'Mining' Cycle: *Prospect to Product*



Resource Assessment (Prospecting)



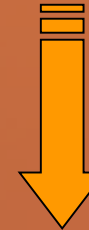
Global Resource Identification



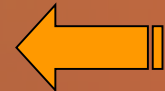
Local Resource Exploration/Planning



Mining



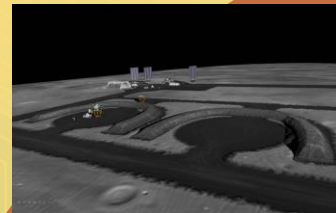
Crushing/Sizing/
Beneficiation



Processing



Atmosphere
Collection



Site Preparation &
Infrastructure Emplacement



Waste
Remediation

Spent Material
Removal

**Communication
& Autonomy**



**Maintenance
& Repair**

Power



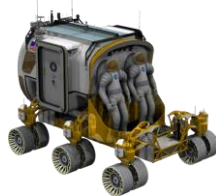
Propulsion



Life Support & EVA



Depots

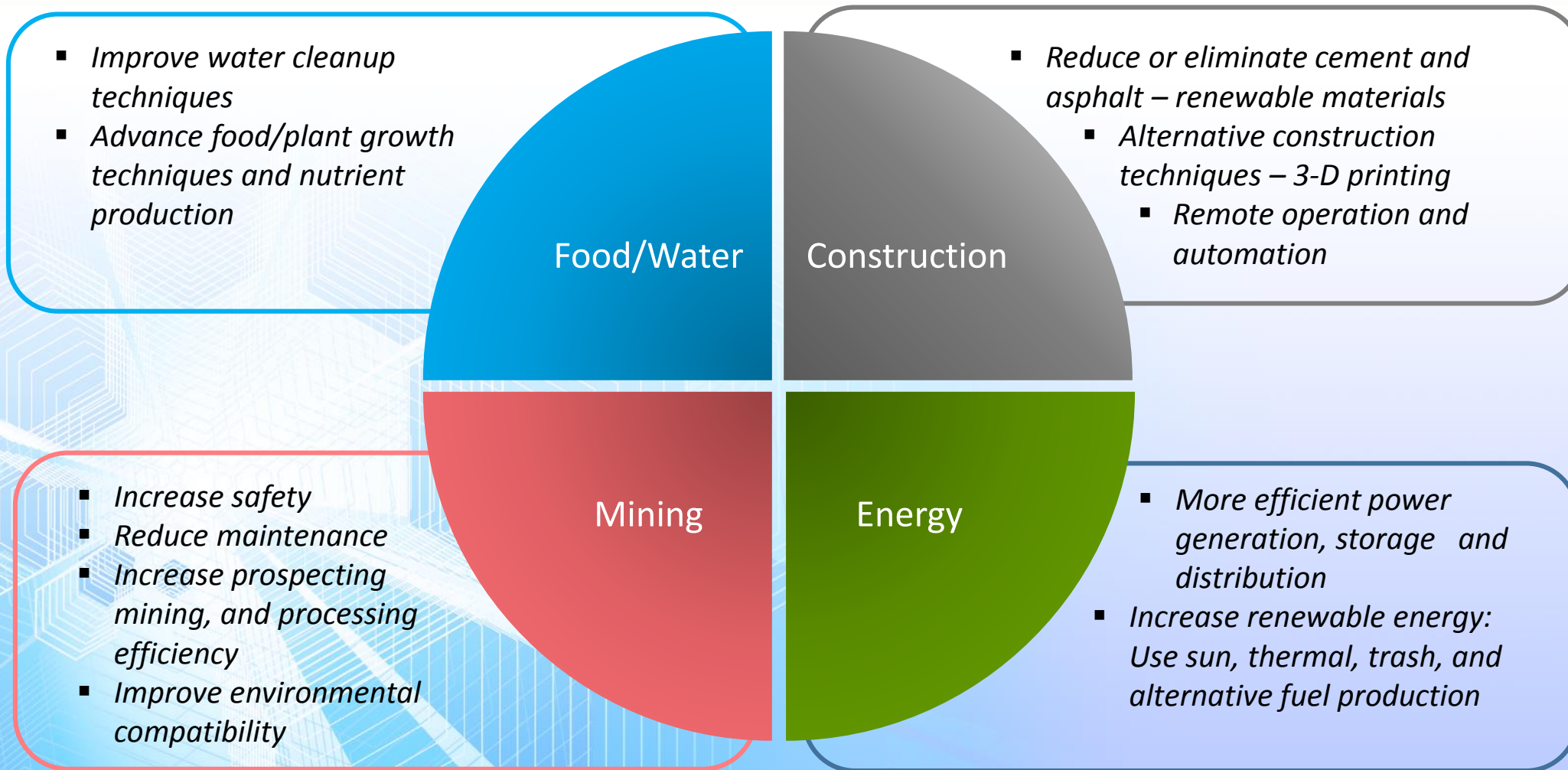


Product Storage & Utilization

Just like Terrestrial Industry, NASA needs to understand and develop all the steps in the mining cycle from Prospecting to Product Delivery to achieve *Sustained* and *Affordable* ISRU Capabilities

ISRU Is Synergistic with Terrestrial Needs

JSC Engineering: HSF Exploration Systems Development



**Promote Reduce, Reuse, Recycle, Repair, Reclamation
...for benefit of Earth, and living in Space.**

The Economics of ISRU



Whether a resource is 'Useful' is a function of its *Location* and how *Economical* it is to extract and use

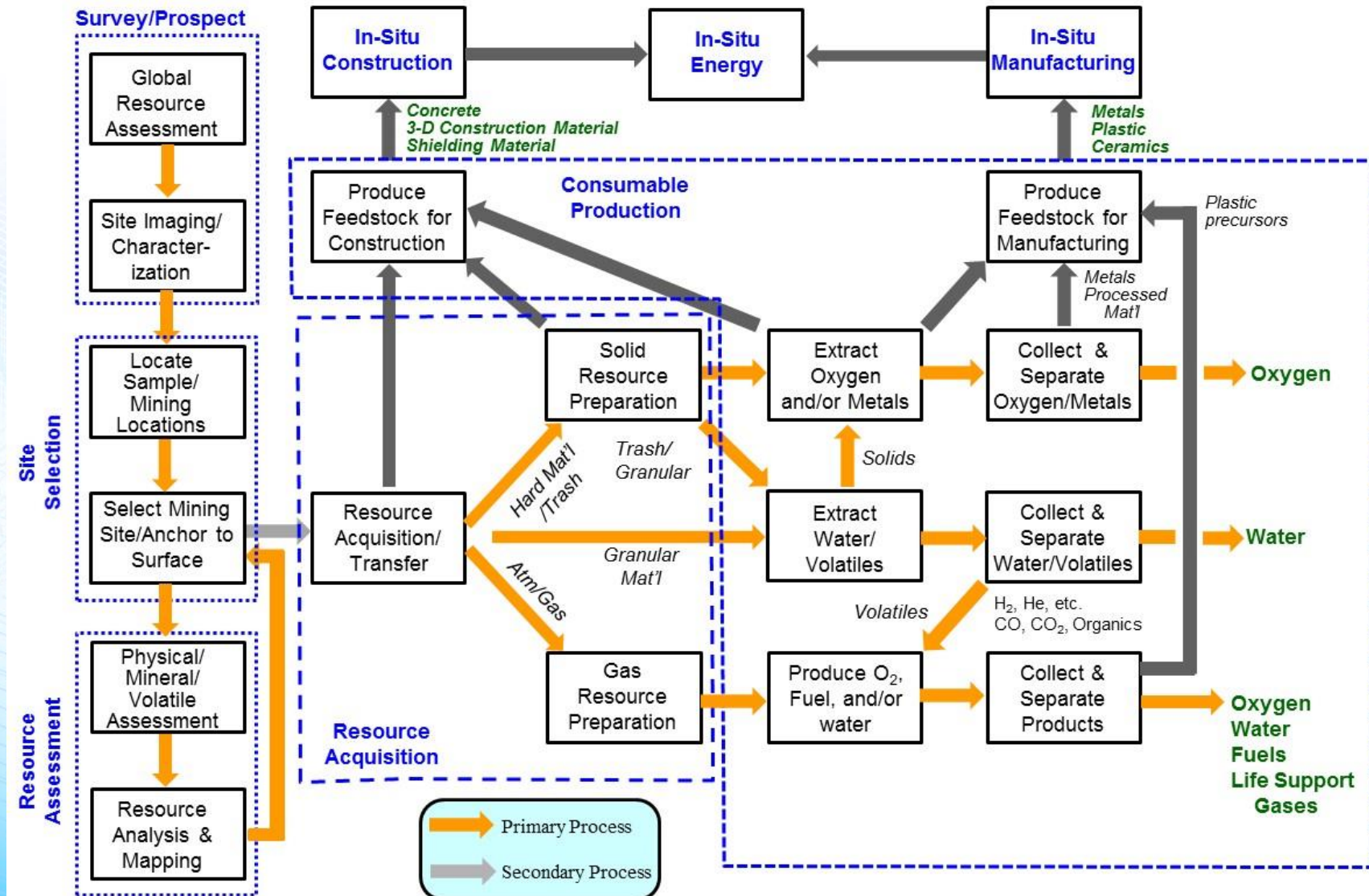
■ Location

- Resource must be assessable: slopes, rock distributions, surface characteristics, etc.
- Resource must be within reasonable distance of mining infrastructure: power, logistics, maintenance, processing, storage, etc.
- Resource must be within reasonable distance of transportation and delivery of product to 'market': habitats, landers, depots, etc.

■ Resource extraction must be 'Economical'

- **Concentration and distribution of resource and infrastructure needed to extract and process the resource allows for Return on Investment (ROI) for:**
 - **Mass ROI** - Mass of equipment and unique infrastructure compared to bringing product and support equipment from Earth
 - **Cost ROI** - Cost of equipment and unique infrastructure compared to elimination of launch costs or reuse of assets (ex. reusable vs single use landers)
 - **Mission ROI** - Extra exploration or science hardware, extended operations, newly enabled capabilities
 - **Crew Safety ROI** - Increased safety compared to limitations of delivering product from Earth: life support, radiation shielding, delivery delay, etc.
 - **Time ROI** - Time required to achieve 1 or more ROIs.
- **Amount of product needed justifies investment in extraction and processing**
 - Requires near and long-term view of exploration and commercialization strategy to maximize benefits (phasing)
- **Transportation of product to 'Market' (location of use) must be considered**
 - Use of product at extraction location most economical
 - Resource used may be a function of mission phase and amount needed

ISRU Capability-Function Flow Chart



Challenges for ISRU Development and Implementation

Many common with Terrestrial Industry



Space Resource Challenges

- What resources exist at the site of exploration that can be used?
 - Are there enough of the right resources; Return on Investment
- What are the uncertainties associated with these resources?
 - Form, amount, distribution, impurities/contaminants
- How to address planetary protection requirements?
 - Environmental protection, remediation

ISRU Operation Challenges

- How to operate in extreme environments, including temperature, pressure, dust, and radiation?
- How to achieve long duration, autonomous operation and failure recovery?
- How to operate in low gravity or micro-gravity environments?
 - Anchoring/weight-on-bit
 - Friction, cohesion, and electrostatic forces may dominate in micro-g

ISRU Technical Challenges

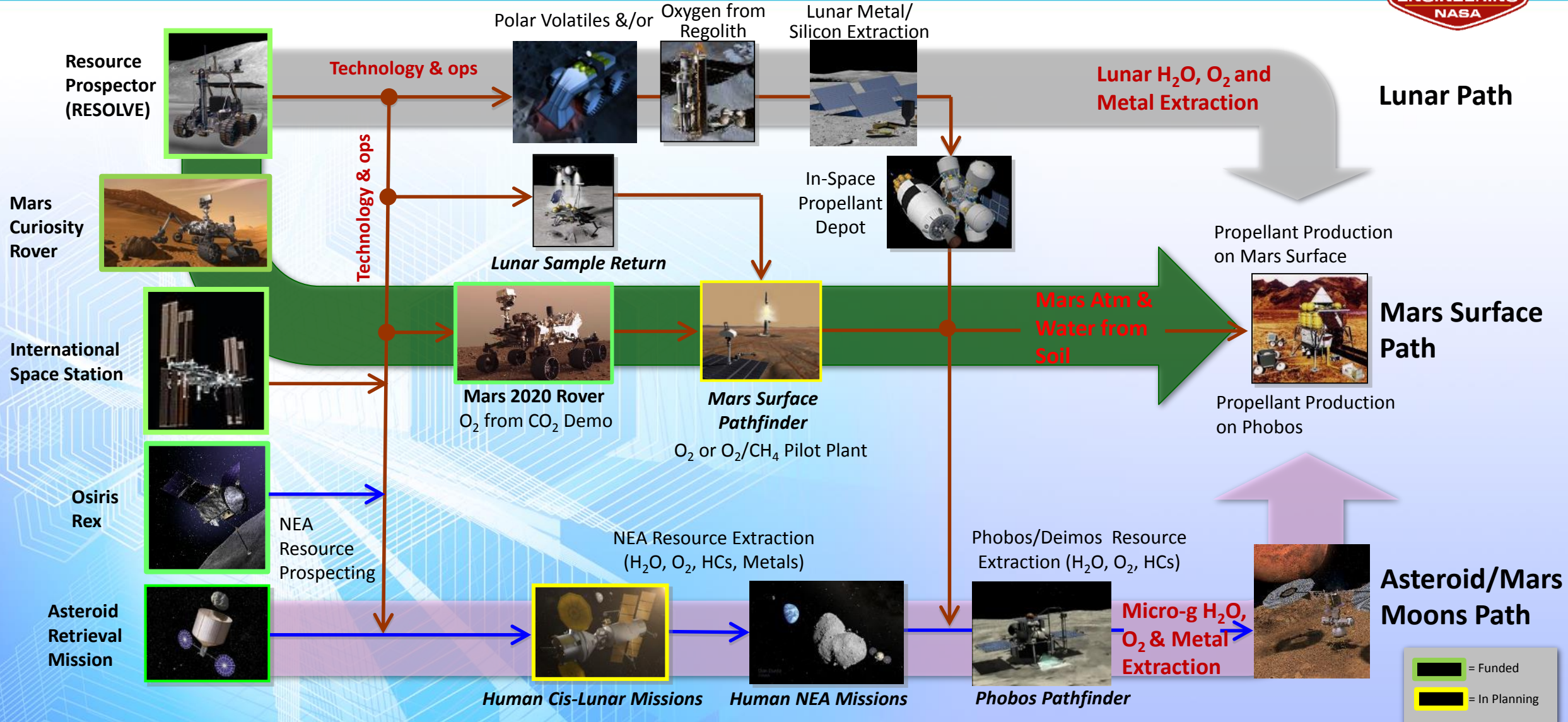
- Is it technically feasible to collect, extract, and process the resource?
- How to maximize performance/minimize mass
- How to achieve high reliability and minimal maintenance requirements?
- How to minimize power through thermal management integration and taking advantage of environmental conditions?

ISRU Integration Challenges

- How to optimize at the architectural level rather than the system level?
- How are other systems designed to incorporate ISRU products?
- How to manage the physical interfaces and interactions between ISRU and other systems?
- How to establish and grow production and infrastructure over time to achieve immediate and long-term Returns on Investment

Overcoming these challenges requires a multi-discipline and integrated approach

Possible NASA ISRU Pathways to Mars



Mars mineral resources of interest for ISRU / CE



Resource	Potential Mineral Source		Reference
Water, Hydration/ Hydroxyl	Gypsum – (CaSO ₄ .2H ₂ O) Jarosite – (KFe ³⁺ ₃ (OH) ₆ (SO ₄) ₂) Opal & hydrated silica – (SiO ₂ .nH ₂ O) Phyllosilicates Other hydrated minerals (TBR)		Horgan, et al.(2009), Distribution of hydrated minerals in the north polar region of Mars, J. Geophys. Res., 114, E01005 Mustard et al.(2008), Hydrated silicate minerals on Mars observed by the Mars Reconnaissance Orbiter CRISM instrument, Nature 454, 305-309
Water, Ice	Icy soils Glacial deposits		Mellon & Feldman (2006) Dickson et al. (2012)
Iron*	Hematite Magnetite Laterites	Jarosite Triolite Ilmenite	Ming et al. (2006), Geochemical and mineralogical indicators for Aqueous processes in Columbia Hills of Gusev Crater, Mars” JGR 111, E02S12 Poulet et al. (2007), Martian surface mineralogy from OMEGA/Mex: Global mineral maps” JGR 112, E08S02
Aluminum*	Laterites Aluminosilicates	Plagioclase Scapolite	
Magnesium*	Mg-sulfates, Mg-rich olivines, Forsterite		
Silicon	Pure amorphous silica Hydrated silica Phyllosilicates		Rice et al. (2010), “Silica-rich deposits and hydrated minerals at Gusev Crater, Mars: Vis-NIR spectral characterization and regional mapping” Icarus 205 (2010) 375–395
Titanium*	Ilmenite, Titanomagnetite		Ming et al. (2006), JGR 111, E02S12

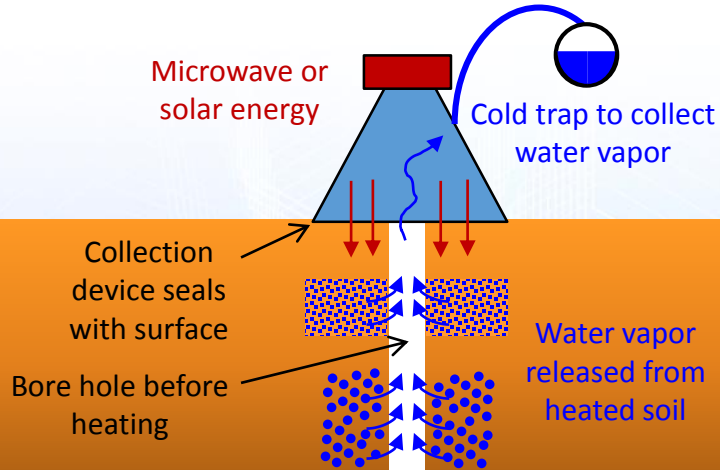
* Mineable metals may be found in geologic features such as: dikes, grabens, impact craters

	Oxides (Wt%)													Elements (ppm)			
	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Cr ₂ O ₃	Cl	SO ₃	Ni	Zn	Br	Ge
MER Spirit – Laguna Soils, Panda Subclass	46.8	0.79	10.5	16.1	0.33	9.6	6.2	3	0.38	0.75	0.35	0.6	4.6	684	190	42	6
Rocknest Soil (Portage)	43.0	1.2	9.4	19.2	0.42	8.7	7.3	2.7	0.49	0.95	0.49	0.69	5.5	456	326	34	
Mojave Mars Simulant	49.4	1.09	17.1		0.17	6.1	10.5	3.3	0.48	0.17	0.05		0.1	118	71		0.07

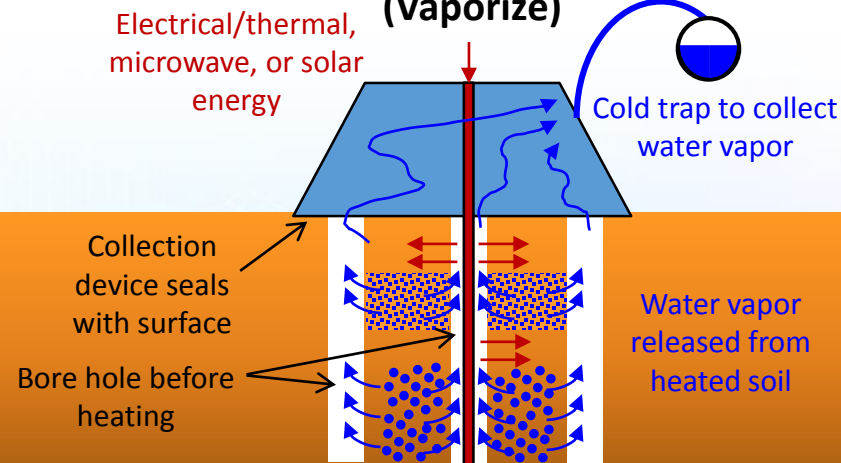
In Situ Water Extraction vs Excavation and Processing



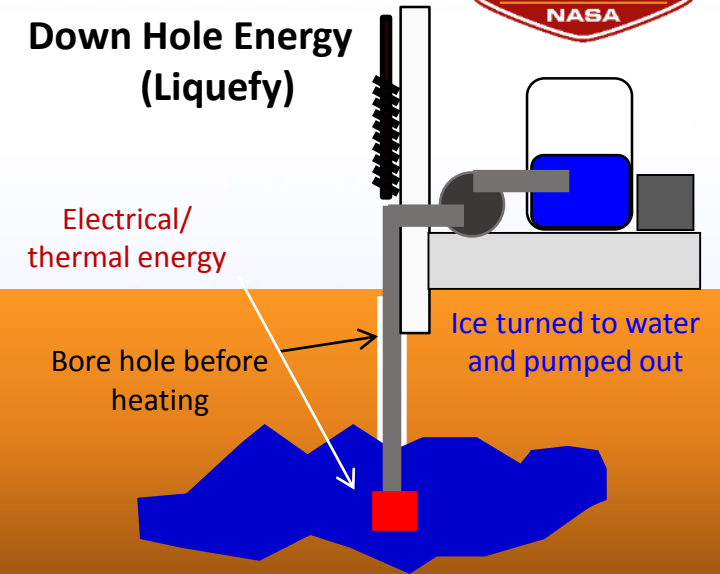
Beamed Energy



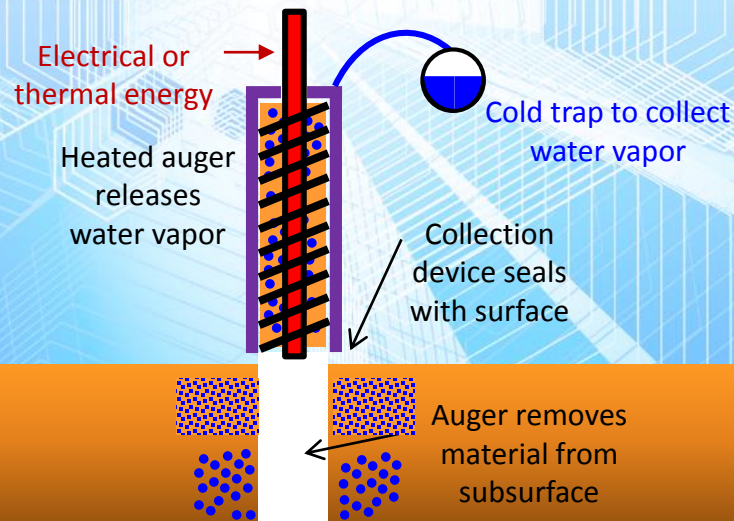
Down Hole Energy (Vaporize)



Down Hole Energy (Liquefy)

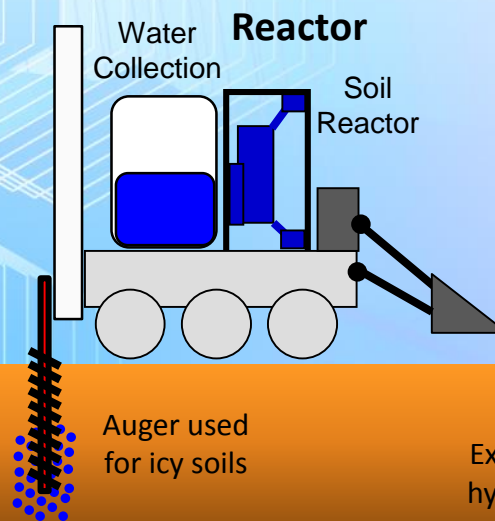


Combined Excavator/Reactor

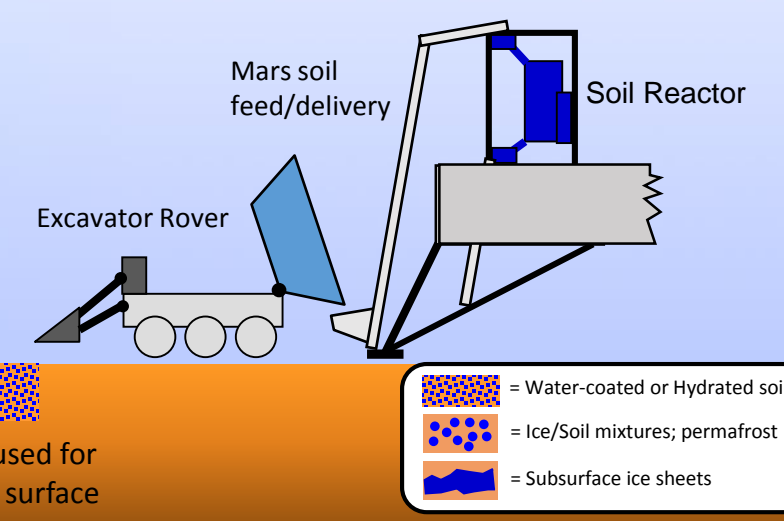


On Rover

Separate Excavator/Soil Reactor



Excavation & Delivery to Stationary Reactor

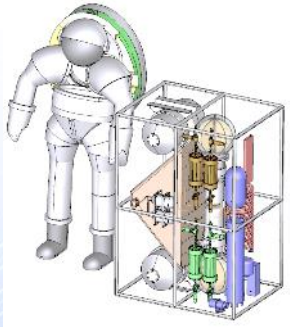


- = Water-coated or Hydrated soils
- = Ice/Soil mixtures; permafrost
- = Subsurface ice sheets

Mars ISRU: Atmosphere & Water Resource Attributes



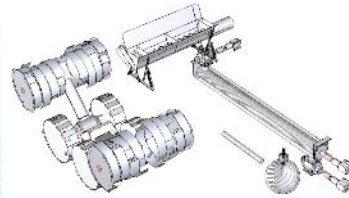
Atmosphere Processing



Atmosphere

- Pressure: 6 to 10 torr (~0.08 to 0.1 psi);
- >95% Carbon Dioxide
- Temperature: +35 C to -125 C
- **Everywhere on Mars;** Lower altitude the better
- Chemical processing similar to life support and regenerative power

Granular Regolith Processing for Water



Mars Garden Variety Soil

- **Low water concentration 1-3%**
- **At surface**
- **Granular; Easy to excavate**
- 300 to 400 C heating for water removal
- Excavate and transfer to centralized soil processing plant
- **Most places on Mars;** 0 to +50 Deg. latitude

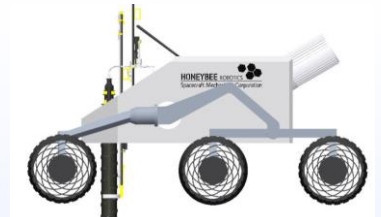
Gypsum/Sulfate Processing for Water



Gypsum or Sulfates

- Hydrated minerals 5-10%
- **At Surface**
- **Harder material:** rock excavation and crushing may be required
- **150 to 250 C heating for water removal**
- **Localized concentration in equatorial and mid latitudes**

Icy Regolith Processing for Water



Subsurface Ice

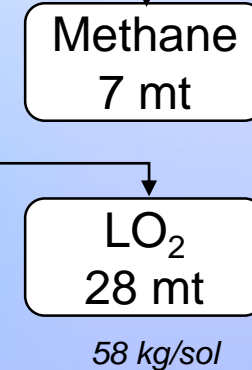
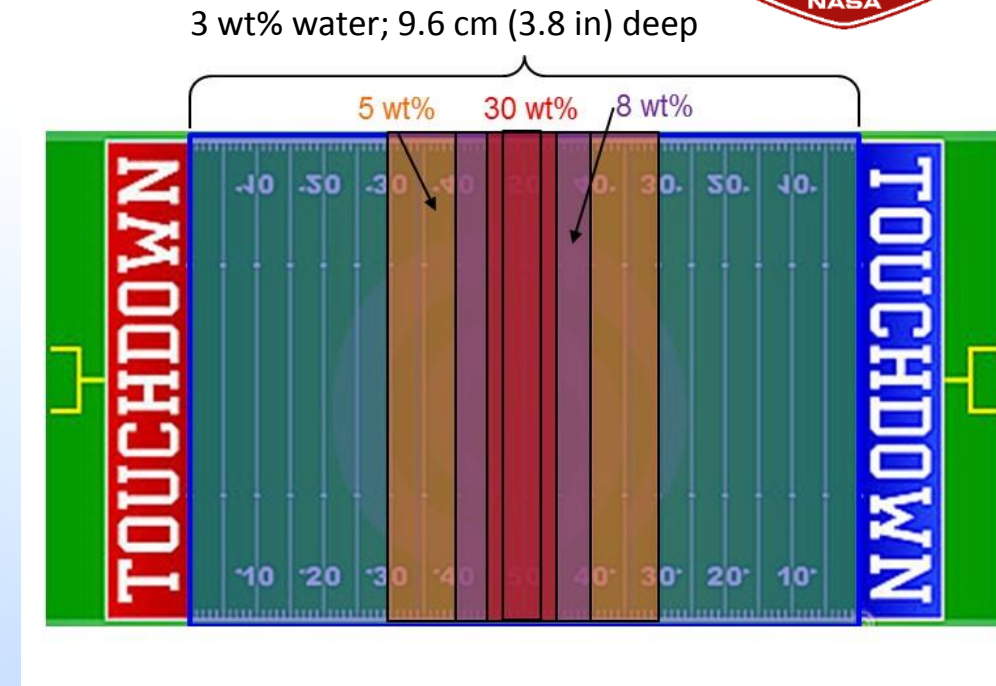
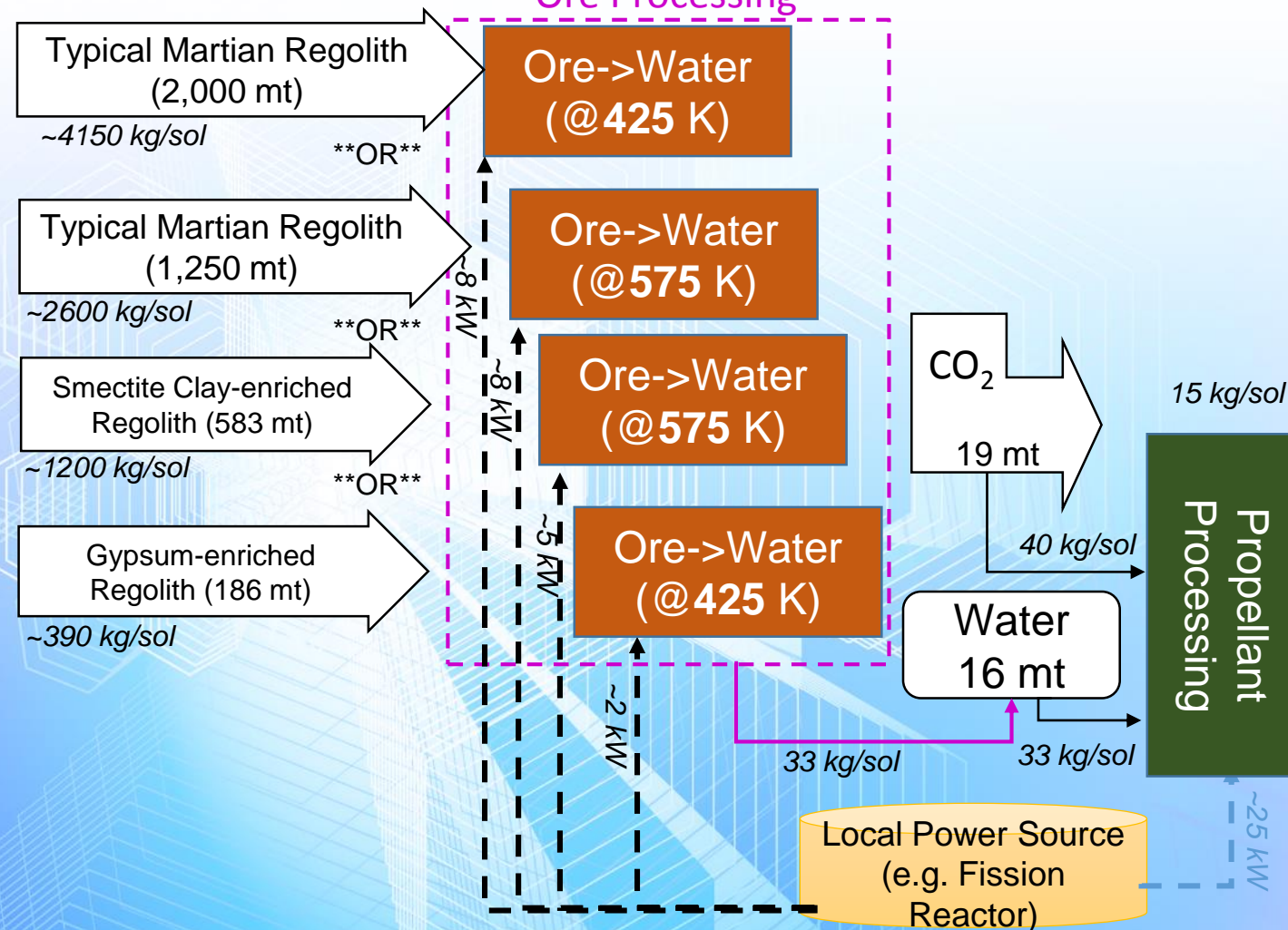
- **90%+ concentration**
- **Subsurface glacier or crater:** 1 to 3 m from surface possible
- Hard material
- **100 to 150 C heating for water removal**
- Downhole or on-rover processing for water removal
- **Highly selective landing site for near surface ice or exposed crater; >40 to +55 Deg. latitude**

Increasing Complexity, Difficulty, and Site Specificity

Mars ISRU Processing Rates for Ascent Vehicle Propulsion



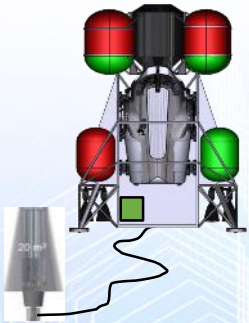
Mars Soil/Water Options



ISRU "Rich" Architecture



Ascent O₂ Production



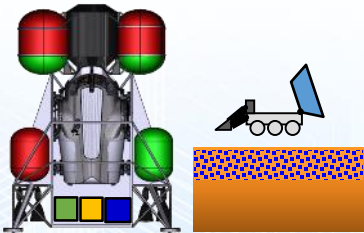
ISRU Processes

- Atm. CO₂ to O₂

ISRU Products

- 20 to 24 mT O₂

Ascent O₂ & CH₄ Production



ISRU Processes

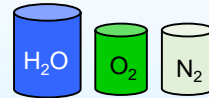
- Atm. Processing
- H₂O Processing
- Soil Processing for H₂O

ISRU Products

- 20 to 24 mT O₂
- 6 to 7 mT CH₄
- 14 mT H₂O (used)

Life Support Backup (DRM 3)

- 4500 kg of O₂
- 3900 kg of N₂
- 23,200 kg of water (H₂O)



Consumable Depot

Preposition Consumables To Extend Traverses in Exploration Zone

- Reuse Surface Pathfinder lander design with ISRU to preposition crew consumables at sites of exploration interest away from Habitat



Increasing Usage and Architecture Impact

Mobile Power

- Fuel cell and reactant storage instead of batteries & carrying nuclear reactor
- Amount: 1000 kg O₂ & 350 kg CH₄ per 14 day traverse



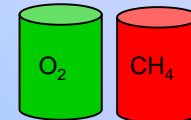
PUP



Crewed Rover

Habitat Backup Power

- Fuel Cell reactants for Dust Storms
- 14.8 KW at up to 120 days
- Amount: 21 mT O₂ & 9 mT CH₄



Hoppers & Reusable Landers

- Reuse previous landers to deliver cargo/crew to other destinations
- Amount: TBD based on distance and payload



Landing Pad and Road Construction

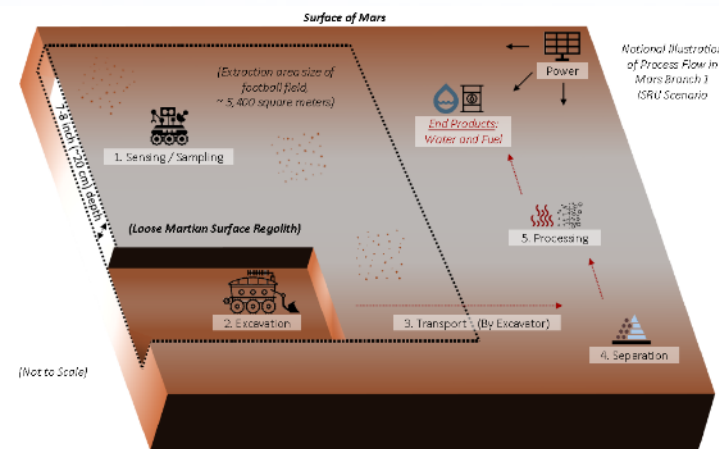
Radiation Shielding & Habitat Burial

Habitat Construction

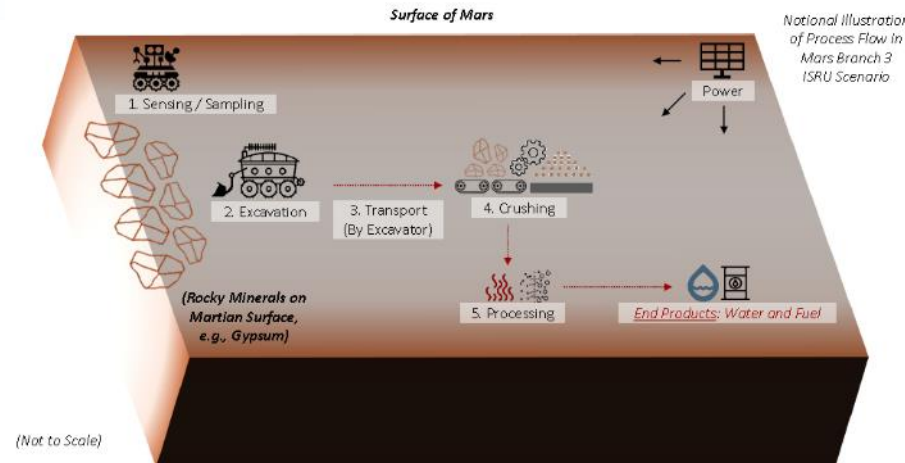
Extra-Terrestrial Mining Operations



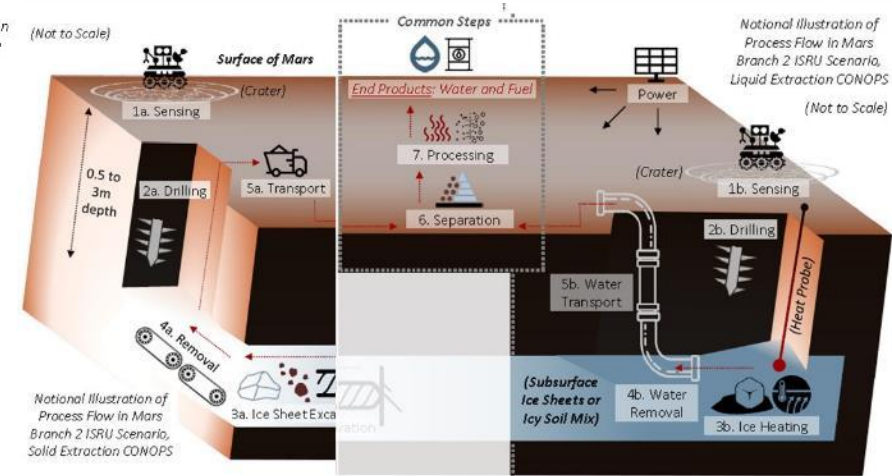
Granular Soil Resource



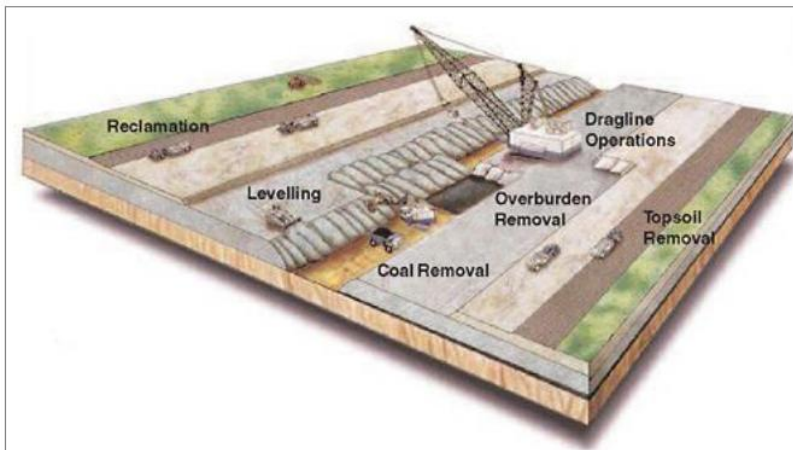
Hard Mineral Resource



Icy Resource



Surface Mining



Quarry Mining

